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CP violation and CKM measurements in Bottom and Charm decays at CDF

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S. D'Auria [a*]
for the CDF collaboration

[a] Department of Physics and Astronomy,
University Avenue G12 8QQ Glasgow, U.K.

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We present preliminary measurements of branching ratios and CP asymmetries in 5 charmless decay modes of the B mesons and precise measurement of direct CP asymmetry in Cabibbo-suppressed charm decays. We used 180pb^{-1} of the hadronic-b data stream at CDF at Tevatron Run II. The decay mode $B_s \to \phi\phi$ has been observed for the first time, with a branching fraction of $(1.4 \pm 0.6 \pm 0.2 \pm 0.5) \times 10^{-5}$. We also present the first measurement of the branching fraction $\mathcal{B}(B_s \to K^+K^-) = (3.56 \pm 0.57 \pm 0.50 \pm 0.43) \times 10^{-5}$.

1. Introduction

CP violation in weak decays of B mesons is one of the least tested parts of the standard model. Within this model CP violation is due to the fact that not all the elements of the CKM matrix can be chosen to be real at the same time. Measuring CP asymmetries translates into precision measurements of CKM elements. In addition, some extensions of the standard model foresee other sources of CP violation, which are best searched for where standard model effects are small, hence in the B and D meson decays.

Hadron collisions are an abundant source of heavy flavour hadrons. At Tevatron, with $p\bar{p}$ collisions at a centre of mass energy of $\sqrt{s}$ = 1.96 TeV the b-hadron cross section in central rapidity range is 29.4 μb [1]. This gives us a big opportunity to study heavy flavour decays, but we have to disentangle them from a light-flavour QCD background that is 3 orders of magnitude larger. In order to measure the asymmetry we first have to establish the signal and measure the branching ratio with respect to other decays with the same topology. In this paper we restrict our range to decays that have no neutral pion in the final state and have 2, 3 and 4 charged tracks. For B mesons we have looked at self tagged decays, where the final state indicates the meson flavour, while for charmed mesons we have selected D^0 coming from D^* decays, where the sign of the soft pion indicates the flavour of the D^0.

2. The event selection

The events were selected by the hadronic-b trigger, that makes use of the Silicon Vertex Trigger (SVT) [2,3]. The on-line resolution of the level-2 silicon tracking is 35 μm on the track impact parameter. The trigger requirements are: 2 opposite charged tracks with a $P_t > 2.0$ GeV/c and an impact parameter of 120 μm, a scalar $\Sigma P_t > 5.5$ GeV/c and a projected decay length larger than 200 μm. For the 2 charged track final state the polar angle difference was required to be $20^\circ < \Delta\phi < 135^\circ$ while for multi-track final states was $2^\circ \leq \Delta\phi \leq 90^\circ$. In all the analyses

*Guest Scientist at FNAL, Mail Stop 318, PO box 500, Batavia, IL, 60510, U.S.A. e-mail dauria@fnal.gov

reported here we required both trigger tracks to be in the final state candidate.

3. B_s to Vector-Vector charmless decay

By comparing the angular distributions from various Vector–Vector decays the angles α and γ can be extracted [4]. CDF can contribute independent measurements to the $B_{u,d}$ decays in addition to the B-factories and can open the window on B_s decays.

$B_s \to J/\Psi\phi$ is a well established signal [6] that is best studied at CDF using events from the muon trigger stream. In the hadronic B trigger this is our reference channel for other VV decays. The decay $B_s \to \phi\phi$ has pure penguin diagram contributions $b \to ss\bar{s}$ and has never been observed before. Because of the narrow ϕ resonance it can be detected with virtually no background in spite of the expected low branching fraction. We

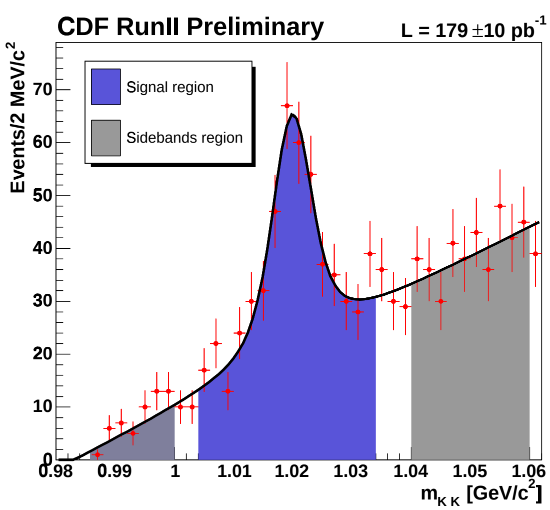

Figure 1. Invariant mass of the ϕ candidates.

performed a blind analysis, optimizing the cuts by maximizing the score function $\frac{S}{1.5+\sqrt{B}}$ [5], where S is the number of signal Monte Carlo events and B is the number of background events from the sideband of the ϕ mass plot, as shown in fig. 1. Different trigger topologies gave slightly different optimal cut values. A complete analysis will be

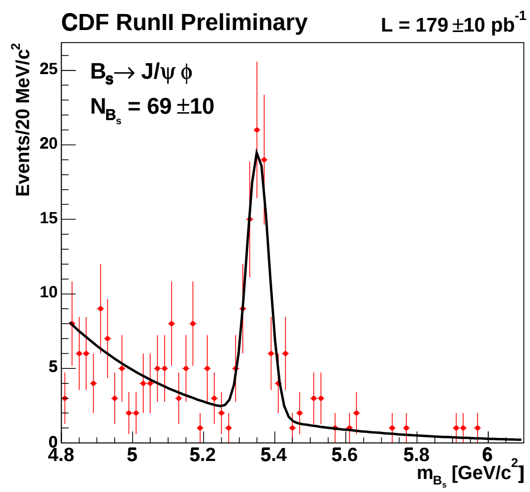

Figure 2. Invariant mass plot for the $B_s \to J/\Psi\phi$ candidates in the CDF hadronic trigger.

described in a forthcoming paper. As an indication, the global cuts variables and values are: projected transverse decay length $L_{xy} > 350\mu m$, distance of the reconstructed meson track from the primary vertex $|d_0(B_s)| < 80\mu m$, vertex $\chi^2 < 10$, $P_t(\phi) > 2.5$ GeV/c. The cuts on the control sample were optimized separately, giving the mass plot shown in fig. 2. We removed the candidates with $J/\Psi \to e^+e^-$ decay by requiring track matching with muon segments. The invariant mass plot for $B_s \to \phi\phi$ candidates is shown in fig. 3: we observe 8 events, with a background of 0.75 events. To extract the relative branching fraction we made use of Monte Carlo samples that realistically simulate the detector in its various configurations, such as beam line position, component functionality and trigger tables. We calculated trigger, reconstruction and analysis efficiency ratios with respect to the reference chan-

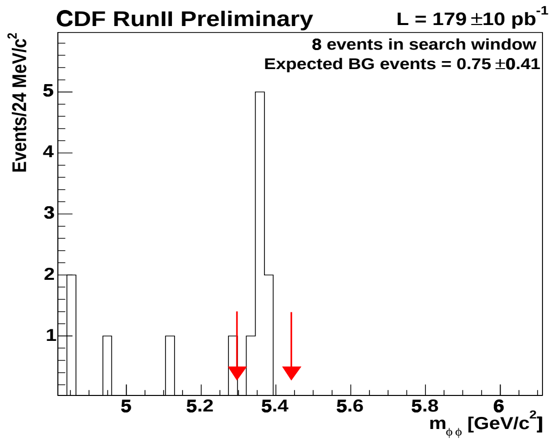

Figure 3. Invariant mass for the $B_s \to \phi\phi$ candidates. The arrows indicate the region that was blinded during cut optimization.

nel. The relative branching ratio is given by:

$$\frac{\mathcal{B}(B_s \to \phi\phi)}{\mathcal{B}(B_s \to J/\Psi\phi)} = \frac{N_{\phi\phi}}{N_{J/\Psi\phi}}\epsilon_R\frac{\mathcal{B}(J/\Psi \to \mu^+\mu^-)}{\mathcal{B}(\phi \to K^+K^-)} \quad (1)$$

where $\epsilon_R = \frac{\epsilon_{J/\Psi\phi}}{\epsilon_{\phi\phi}}$ is the overall relative efficiency. The main sources of systematic errors are the decay polarization and the trigger efficiency (μ vs. K). The value of $\Delta\Gamma_s/\Gamma_s = (12 \pm 6)\%$ was used to calculate the systematics due to different lifetimes of CP even and odd states. The final result is

$\mathcal{B}(B_s \to \phi\phi) = (1.4 \pm 0.6_{stat} \pm 0.2_{sys} \pm 0.5_B)10^{-5}$

The last error derives from the reference channel branching ratio uncertainty. This BR value is considerably lower than predictions based on QCD Factorization [7].

4. B^+ to Vector–Scalar charm-less decays

These decays are interesting to search for possible large direct asymmetries. Also in this case the largest contribution comes from a penguin diagram $b \to ss\bar{s}$, as the tree annihilation diagram is double Cabibbo suppressed.

The analysis of this decay channel is very similar to the one described in the previous section: Monte Carlo samples and ϕ side-band data have been used to optimize the analysis cuts. The control sample is $B^{\pm} \to J/\psi K^{\pm}$, that has the same 3-track topology, where we selected the $\mu^+\mu^-$ component. The main analysis cuts are: $L_{xy} > 350\mu$m, $P_t(K) > 1.3$ GeV/c, $\chi^2_{xy} < 8$, $|d_0(K)| \geq 120\mu$m and isolation $I_{R<1.0} \geq 0.5$. We observe 47 ± 8 candidates. With this statistics it is possible to perform a preliminary measurement of the direct asymmetry. An un-binned "extended" likelihood function has been formed, using the 3-track invariant mass, the mass of the two tracks that form a ϕ, the ϕ polarization and the particle ID. The latter is based on the measurement of ionization in the central tracking chamber (COT), as shown in fig. 8. We assumed these 4 variables are independent, so the probability density (PDF) used in the likelihood fit is the product of the individual PDF that have been calculated using Monte Carlo samples. For the mass distributions we have modeled the combinatorial background as well as the physical background that is due to partially reconstructed channels. The fit

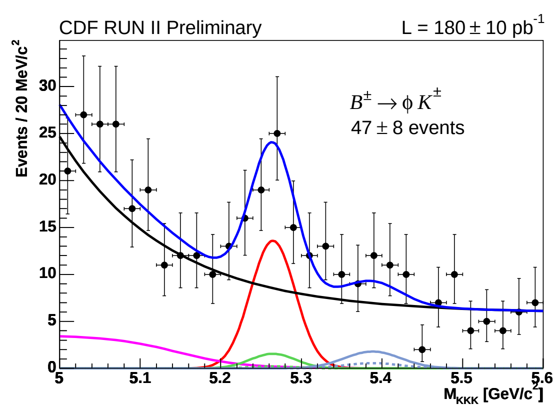

Figure 4. Invariant mass of the KKK candidates. The lower curves in gray are from physical background: partially reconstructed decays, $f_0K^{\pm}$ and $K^{*0}\pi^{\pm}$.

is performed simultaneously on B^+ and B^- candidates, returning the total number of events and

Table 1
Branching fraction results.

Decay	Reference channel	Relative $\mathcal{BR}(\%)$	Absolute $\mathcal{BR}$
$B_s \to \phi\phi$	$B_s \to J/\psi\phi$	$1.4 \pm 0.6 \pm 0.2$	$(1.4 \pm 0.6 \pm 0.2 \pm 0.5) \times 10^{-5}$
$B^\pm \to \phi K^\pm$	$B^\pm \to J/\psi K^\pm$	$0.72 \pm 0.13 \pm 0.07$	$(7.2 \pm 1.3 \pm 0.7) \times 10^{-6}$
$B_d^0 \to \pi^+\pi^-$	$B_d^0 \to K^\pm\pi^\mp$	$24 \pm 6 \pm 5$	$(4.4 \pm 1.1 \pm 0.9 \pm 0.3) \times 10^{-6}$
$f_s B_s \to K^+K^-$	$f_d B_d^0 \to K^\pm\pi^\mp$	$50 \pm 8 \pm 7$	$(3.56 \pm 0.57 \pm 0.50 \pm 0.38 \pm 0.21) \times 10^{-5}$
$f_d B_d^0 \to \pi^\pm\pi^\mp$	$f_s B_s \to K^+K^-$	$48 \pm 12 \pm 7$	–
$D^0 \to K^+K^-$	$D^0 \to K^\pm\pi^\mp$	$9.92 \pm 0.11 \pm 0.12$	$(3.770 \pm 0.042 \pm 0.046 \pm 0.09) \times 10^{-3}$
$D^0 \to \pi^+\pi^-$	$D^0 \to K^\pm\pi^\mp$	$3.594 \pm 0.054 \pm 0.040$	$(1.366 \pm 0.021 \pm 0.015 \pm 0.032) \times 10^{-3}$
$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$	$276.0 \pm 4.0 \pm 3.4$	–

The first uncertainty is statistical the second is systematic, the third one, if present, is due to the branching fraction uncertainty in the reference mode from ref. [8]. The fourth is due to $f_s/f_d = (0.26 \pm 0.03)$.

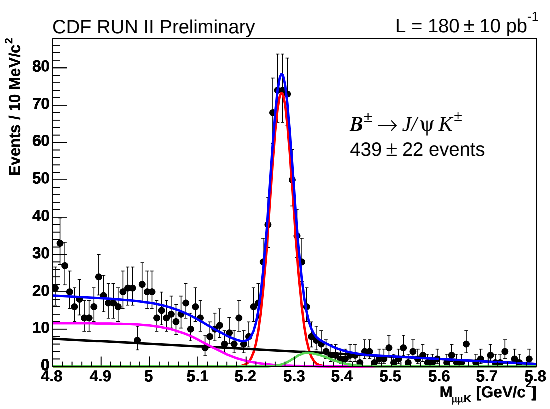

Figure 5. Invariant mass plot for the $B^\pm \to J/\psi K^\pm$ candidates in the CDF hadronic trigger.

the direct asymmetry

$$A_{CP} = \frac{\Gamma(B^- \to \phi K^-) - \Gamma(B^+ \to \phi K^+)}{\Gamma(B^- \to \phi K^-) + \Gamma(B^+ \to \phi K^+)} \qquad (2)$$

We assumed that there is no production asymmetry. The fit projection on the candidate mass variable is shown in fig. 4, the asymmetry is reported in table 2. For comparison in $B^\pm \to J/\psi K^\pm$ we observe (439 ± 22) events in the same data stream (fig. 5). The relative branching fraction has been calculated using a formula similar to (1). Using the PDG-04 value for the control sample branching ratio we obtain $\mathcal{B}(B^\pm \to \phi K^\pm) = (7.2 \pm 1.3 \pm 0.7) \times 10^{-6}$ which is in agreement with the Belle [11], BaBar [12] and CLEO [13] results and has a comparable precision.

5. $B_{u,s}$ to Scalar–Scalar charm-less decays

Also in these decays, where the final state is a $\pi^\pm$ or a $K^\pm$, penguin diagrams are important or dominate. In the case of $B_d^0 \to \pi^+\pi^-$ and of $B_s \to K^+K^-$ the presence of penguin contributions make it difficult to extract CKM parameters. However, measuring the time-dependent CP asymmetry of both decays it is possible to determine the CKM angle γ with much smaller theoretical uncertainties [14]. In addition, it is possible to measure the direct CP asymmetry of the self tagging mode $B_d^0 \to K^+\pi^-$, that has mainly $b \to su\bar{u}$ contributions, thus complementing the measurement of asymmetry in $b \to ss\bar{s}$ reported above.

To reach these goals we first need to select the two body decays of b-mesons and then disentangle the signal of the various decays. The optimized cuts to select 2-body decays include $L_{xy} \geq 300\mu$m, $|d_0(B)| \leq 80\mu$m and isolation $I_{R<1.0} \geq 0.5$. The mass peak that we obtain when we assign the pion mass to both charged tracks is shown in fig. 6. We have used the small kinematic difference between the modes as well

Table 2
CP asymmetries results (%)

Decay	This work	Comparison	Ref.
$B_u^{\pm} \to \phi K^{\pm}$	$-7 \pm 17 \pm 5$	4.7 ± 5.2	[9]
$B_d^0 \to K^+\pi^-$	$-4 \pm 8 \pm 1$	-11.3 ± 1.9	[9]
$D^0 \to K^+K^-$	$2.0 \pm 1.2 \pm 0.6$	0.0 ± 2.2	[16]
$D^0 \to \pi^+\pi^-$	$1.0 \pm 1.2 \pm 0.6$	1.9 ± 3.2	[16]

The first error is statistical, the second systematic.

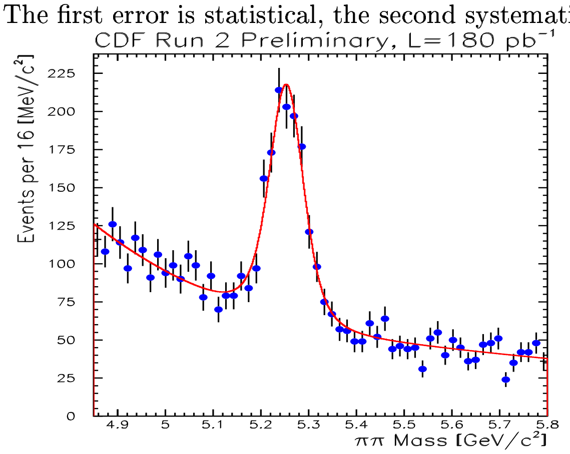

Figure 6. Invariant mass of the two tracks with the π mass hypothesis. The signal peak comes from the overlap of mainly four decay channels of B_d and B_s.

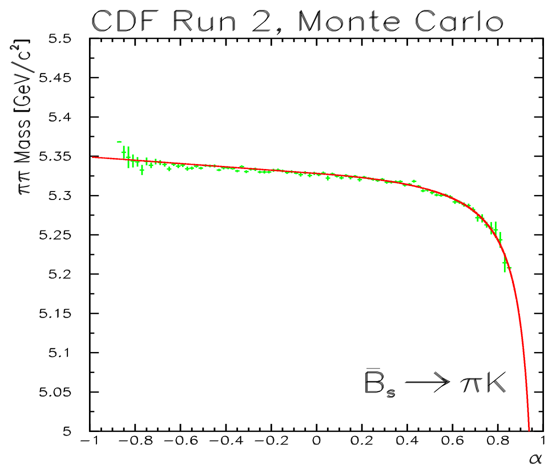

Figure 7. Invariant mass of the 2-tracks, both with (wrong) π mass hypothesis vs. kinematic variable α for the $B_s \to K^+\pi^-$ Monte Carlo sample. In this case the mass depends on α.

as the particle ID from the measurement of track ionization (dE/dx) in the COT to measure the fraction of the decays in the mass peak. As an example, we show in fig. 7 the 2-track invariant mass as a function of the signed momentum imbalance $\alpha = q_1(1 - \frac{p_1}{p_2})$, where p_1 is the lowest of the two track momenta and q_1 is the corresponding charge. If the mass assignment is correct the invariant mass is independent on α, otherwise, as shown in fig. 7, we can use its dependance to make a likelihood function, together with the dE/dx from the COT. The K/π separation using dE/dx is 1.4σ, as shown in fig. 8. The unbinned likelihood fit returns the signal fractions in the peak and the asymmetry of the $B_s \to K^+\pi^-$. We have used realistic Monte Carlo samples with $\Delta\Gamma_s/\Gamma_s = (12 \pm 6)\%$ to estimate the relative efficiency corrections to measure relative branching fractions. The results are shown in table 1 and include the first measurement of $\mathcal{B}(B_s \to K^+K^-)$.

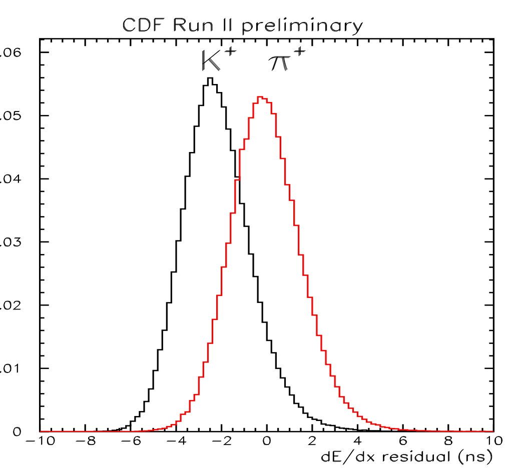

Figure 8. K/π separation using dE/dx in the COT. The pulse height is measured as time over threshold.

6. CP asymmetry in Cabibbo suppressed charm decays

The standard model predicts very small rates of mixing and CP violation in charm decays, ranging from 0.1 to 1%. Observation of CP asymmetry above 1% would indicate evidence for new physics processes. The large charm production cross section at Tevatron [1] and the CDF trigger capability makes it feasible to measure precisely branching fraction and CP asymmetry in charmed mesons.

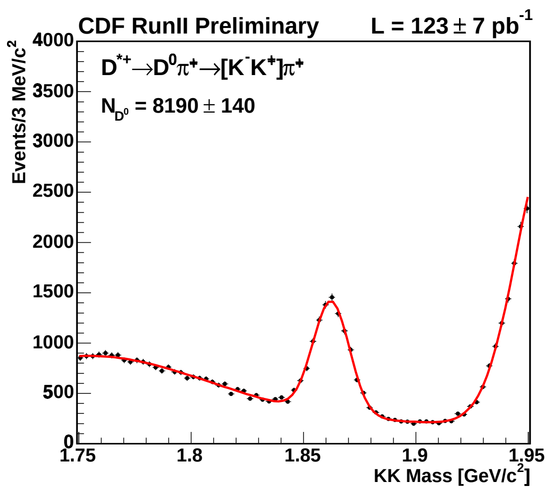

Figure 9. Invariant mass for the K^+K^- candidates after flavour tagging with soft π selection. The peak at large mass value is due to the "reflection" from the Cabibbo–allowed mode, the wide bump in the background is due to decay modes where one or more particles escape detection (e.g. $D^0 \to K^-\pi^+\pi^0$).

We have chosen the Cabibbo suppressed channels $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, while the Cabibbo favoured channel $D^0 \to K^\pm\pi^\mp$ serves as a reference. To tag the flavour, only D^0's from $D^{*\pm} \to D^0\pi^\pm$ are selected, requiring $||M_{D^0} - M_{D^*}| - 145.35| \leq 1.85$ MeV/c^2. The

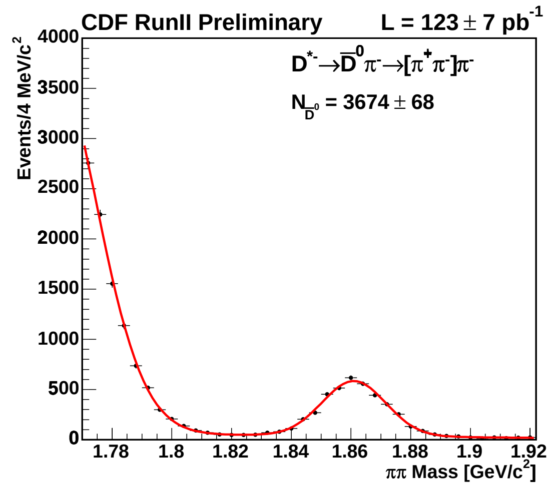

Figure 10. Invariant mass for the $\pi^+\pi^-$ candidates after soft π selection. The tail at low values of invariant mass comes from a peak due to the "reflection" of the Cabibbo–allowed mode, with wrong assignment of mass to the track left by the K.

soft π is allowed to have $p_t \geq 0.4$ GeV/c and $|\eta| < 2$. Analysis cuts include $L_{xy} > 350\mu$m and $|d_0(D^0)| < 100\mu$m. Two of the mass plots, with tag requirement, are shown in fig. 9 and 10. In both cases the signal is very well separated from the Cabibbo allowed decay, that has the wrong mass assignment. In case of $D^0 \to K^-\pi^+$ the partially reconstructed decays contribute with a broad background bump at lower masses values. The ratio of efficiencies has been calculated with realistic Monte Carlo samples, while detector asymmetry effects have been measured from generic tracks from minimum bias events. Checks were performed on the $D^0 \to K^\pm\pi^\mp$, where no asymmetry is expected, and on $K^{*\pm} \to K_s\pi^\pm$, that has all π in the final state. The branching ratios are consistent with the PDG value and are more precise than the best single experiment [15]. As reported in table 2, the direct CP asymmetry is consistent with zero for both channels. We improve the best measurement [16] statistical limit by a factor of two.

7. Conclusions

The trigger based on tracks with impact parameter (SVT) has extended the b-physics potentiality of CDF to channels that contain no lepton in the final state. We can't reliably measure exclusive decays containing π^0 in the hadronic collision environment, but B_s and b-hadrons other than $B_{u,d}$ are available to study. We have measured branching ratios of decays that were never observed before: for $B_s \to \phi\phi$ it is a first step toward measuring angular distributions in this Vector-Vector penguin decay, that will be possible with higher statistics also thanks to the very low background. For $B_s \to K^+K^-$ it will be feasible to measure the time dependent CP asymmetry, together with $B_d^0 \to \pi^+\pi^-$, with larger integrated luminosity when we'll manage to completely characterize the trigger bias on the lifetime and the flavour tagging. Finally, our measurement of the branching fraction of the penguin–dominated decay $B^\pm \to \phi K^\pm$ is compatible with B-factory measurements and has similar precision. We find no evidence for CP asymmetry in any of the decays considered. In particular, for the charmed mesons we have improved the limit on the direct CP asymmetry.

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